Title of Investigation:

Epitaxial Silicon for Cryogenic Bolometers

Leader or Leaders:

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Other In-House Members of the Team:

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Initiation Year:

FY 2003

Aggregate Amount of Funding Authorized in FY 2003 and Earlier Years:

$50,000

FY 2004 Authorized Funding:

$32,500

Actual or Expected Expenditure of FY 2004 Funding:

In-house: $23,500; Contracts: $9,000 (EPI)

Status of Investigation at End of FY 2004:

Completed

Purpose of Investigation:

This investigation was aimed at establishing a new method for producing doped-silicon detectors for infrared astronomy and X-ray astrophysics. Doping is the process used to add impurities to silicon wafers to control their conductivity in specific areas. Silicon detectors on upcoming space missions must operate at temperatures below 4 Kelvin, or 4 degrees above absolute zero, and require precisely doped resistors. Due to the variability of the doping process, about 80-90% of doped silicon wafers do not meet mission requirements and are rejected.

We are investigating the efficacy of replacing the most important, yet troublesome, step of the fabrication process—doping with an ion implanter—with pre-doped material purchased from qualified vendors. The doping method we are investigating is called epitaxial growth. With this process, single-crystal silicon is deposited in a precisely controlled fashion onto a seed crystal. Dopants are introduced during the deposition process and are thought to be uniform throughout the material. In theory, we should be able to produce multiple wafers with identical resistance because the wafers are produced in large batches. Subsequent characterization of one representative wafer from the batch would tell us how resistant the other wafers are. Our aim is determining whether epitaxially grown silicon wafers can be produced of a quality comparable to those produced by ion-implantation. Success in this project would greatly improve semiconductor-detector production yields and performance, reduce fabrication manpower, and improve production schedules.

Accomplishments to Date:

The High Resolution Airborne Wide-band Camera (HAWC), the premier facilities instrument for the Stratospheric Observatory for Infrared Astronomy (SOFIA), and the Astro-E2 X-Ray Spectrometer use detectors with some form of silicon-based resistive element as the sensor. The technology used for HAWC requires a series of nine ion implantations into each silicon wafer to create a precisely tailored net dose. Due to variability of the ion-implantation process, generally only one or two wafers from a starting batch of 10 to 12 fall within the target range. The rest are rejected. The resistance of the doped silicon is extremely sensitive to temperature variation

$$R(T)=R_0 * e^{\sqrt{(T_0/T)}}, \qquad \text{Equation (1)}$$

when R_0 and T_0 are dependent on the concentration of impurities. This dependence makes the doped silicon a very good sensor, but also makes it very difficult to reproduce, as the impurity concentration must fall within a small percent of the target range to be usable.

During FY 2003, we implanted three Silicon-On-Insulator (SOI) wafers with a distribution of implant doses. These wafers provided samples with a desired doping profile. We sent the samples to Lawrence Semiconductor. Lawrence evaluated the samples using Secondary Ion Mass Spectroscopy (SIMS) to establish what it believed to be the doping levels. There was disagreement between these SIMS measurements, the calculated values based on the implanted dose, and the volume of the silicon. To verify the samples, we sent the same material to Charles Evans Analytical Group (CE) to repeat the measurement. The results from CE agreed with our calculations within a small percentage error. Given the uncertainty of the Lawrence SIMS, we asked them to reproduce one of the three doping samples provided. The sample chosen for reproduction is identified as A7 throughout the remainder of investigation. Figure 1 shows the dopant concentration versus depth (in micrometers) for the phosphorous and boron implanted and diffused into silicon. This flat profile, with a sharp drop at the insulating boundary, is the highly desirable profile we wish to reproduce with epitaxial growth.

In FY 2004, Lawrence Semiconductor deposited 1 micron of epitaxial silicon on 0.5 micron thick SOI seed wafers. SOI wafers are composed of three layers: a single crystal silicon handle wafer that is 400 microns thick; 0.2 microns of silicon dioxide insulator; and a top layer of single crystal silicon that is 0.5 microns thick. The top layer, with the epitaxial silicon, is the active region of the wafer and will become the fabricated device. CE measured the sample's profiles. The results also are shown in Figure 1. Several differences become evident when comparing this profile with the implanted witness sample. First, the transition from doped silicon to undoped silicon, located at approximately one-micron depth, is not as sharp as we achieved with implanted and diffused doping. There is a gradual drop of both phosphorous and boron, or a "tail" in the profile. This feature is undesirable because variation in the doping density throughout the silicon is the primary trait we are attempting to avoid to minimize excess electrical noise in the resistor. However, the tail in the profile, while being worse than for implanted and diffused material, is an improvement over HAWC-style implants without diffusion.

Table 1 gives a summary of the average doping concentrations found in the flat portion of the profile for ion-implanted silicon and for epitaxial silicon. Resistors were fabricated at the Goddard Space Flight Center using material from the epitaxial-deposition run. These resistors were tested cryogenically and compared with resistors made from ion-implanted silicon.

A summary of the resistance-versus-temperature performance is shown in the plot of Figure 2. The plot of resistance on the logarithmic vertical axis, versus inverse square root of temperature should

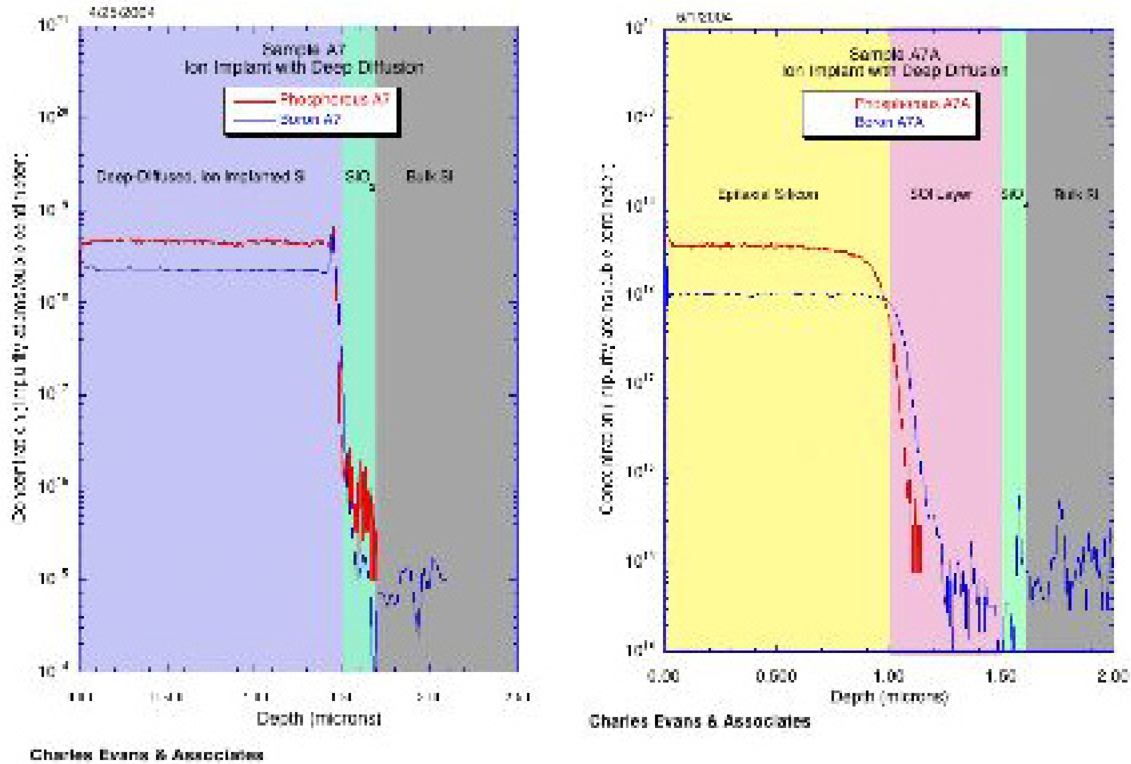

Figure 1. Results of SIMS analysis of two types of doped silicon. Left is deep-diffused ion implantation, similar to the type used for XRS2 6x6 calorimeters. Right is epitaxial silicon on an SOI seed crystal wafer. Measurements were performed by Evans Analytical Group, Sunnyvale, California.

Table 1. Summary of Doping Concentrations

Sample Description	Phos (atoms/cc)	Boron (atoms/cc)	Net (P-B) (atoms/cc)
A7 (Implant/diffuse witness)	4.58e18	2.30e18	2.5e18
A7A (Epitaxial Silicon)	2.76e18	1.03e18	1.73e18

lie on a straight line and fit the relationship shown in equation (1). The ion-implanted resistors fit the function over the temperature range studied. The epitaxial-silicon resistors do not fit the function.

Planned Future Work:

Provided that interest continues, we can continue this work into a Phase A study. We have laid the groundwork for studying the temperature dependence of the resistance of epitaxial silicon. Although our first attempt to prove that the material performs similarly to what we can obtain through in-house ion implantation and deep diffusion has not been successful. However, we do not think that one attempt is adequate to either accept or discard this method, and more work is required.

We plan to obtain another sample of epitaxial silicon with funds remaining from FY 2004. The samples will be produced on SOI wafers with a thinner silicon top layer. In this investigation, we used one-half of one micron, or half the thickness of the epitaxy desired. This allowed room for the dopants to diffuse into the undoped silicon producing the tail in the concentration profile, and producing a slightly downward slope to the “flat” portion of the profile. By starting with thinner

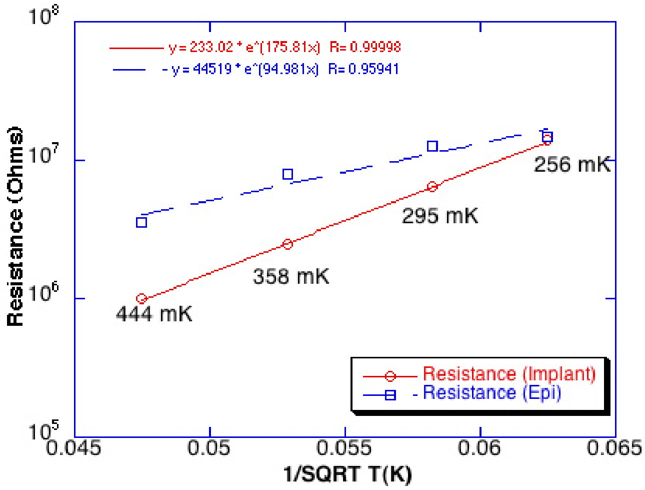

Figure 2. Results of cryogenic testing of epitaxial silicon compared with ion-implanted silicon. The equation is an attempt to fit to the exponential relationship the resistance should follow. The fit is good for ion-implanted silicon. The fit is poor for epitaxial silicon.

seed crystal, we should be able to prevent much of this non-uniformity, which may have caused the epitaxial material to perform poorly. We will retest the new material and determine if the material is of a quality that we can use for detector work. We will abandon the project if it fails to meet our criteria for success.

Summary:

Semiconducting detectors could be made using a new method of well-controlled impurity doping. The new method is reproducible and provides a guaranteed supply of starting material for detector fabrication. The caveat is that we must find good starting material and demonstrate its reproducibility. Unfortunately, we have not accomplished that yet. If we do, the potential payoff to the NASA Goddard Space Flight Center is significant. The yield of usable devices would increase from historical lows of about 10-20% (based on usable processed detector wafers) to nearly 100%. This increased yield would reduce the necessary manpower to fabricate flight wafers and would improve production schedules. In our investigation, we identified a technical risk factor and a possible solution. By starting with thinner seed crystal, we should be able to prevent much of the non-uniformity that may have caused the epitaxial material to perform poorly in our first test. We plan to retest the new material and determine if the material is of a quality that we can use for detector work. If this test fails, additional efforts would be required that are beyond the scope of this effort.